CMC Research at NASA Glenn in 2015: Recent Progress and Plans

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Ceramic & Polymer Composites Branch

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NASA Aeronautics Restructured

Six Strategic Thrusts

Safe, Efficient Growth in Global Operations
- Enable full NextGen and develop technologies to substantially reduce aircraft safety risks

Innovation in Commercial Supersonic Aircraft
- Achieve a low-boom standard

Ultra-Efficient Commercial Vehicles
- Pioneer technologies for big leaps in efficiency and environmental performance

Transition to Low-Carbon Propulsion
- Characterize drop-in alternative fuels and pioneer low-carbon propulsion technology

Real-Time System-Wide Safety Assurance
- Develop an integrated prototype of a real-time safety monitoring and assurance system

Assured Autonomy for Aviation Transformation
- Develop high impact aviation autonomy applications

NASA Aeronautics Programs

address the six strategic thrusts

MISSION PROGRAMS

Airspace Operations and Safety Program

AOSP

- Safe, Efficient Growth in Global Operations
- Real-Time System-Wide Safety Assurance
- Assured Autonomy for Aviation Transformation

Advanced Air Vehicles Program

AAVP

- Ultra-Efficient Commercial Vehicles
- Innovation in Commercial Supersonic Aircraft
- Transition to Low-Carbon Propulsion
- Assured Autonomy for Aviation Transformation

Integrated Aviation Systems Program

IASP

- Flight research-oriented, integrated, system-level R&T that supports all six thrusts
- X-planes/ test environment

SEEDLING PROGRAM

Transformative Aeronautics Concepts Program

TACP

- CAS: High-risk, leap-frog ideas that support all six thrusts
- TTT: Critical cross-cutting tool development and advancement of critical aeronautics technologies
- LEARN: external

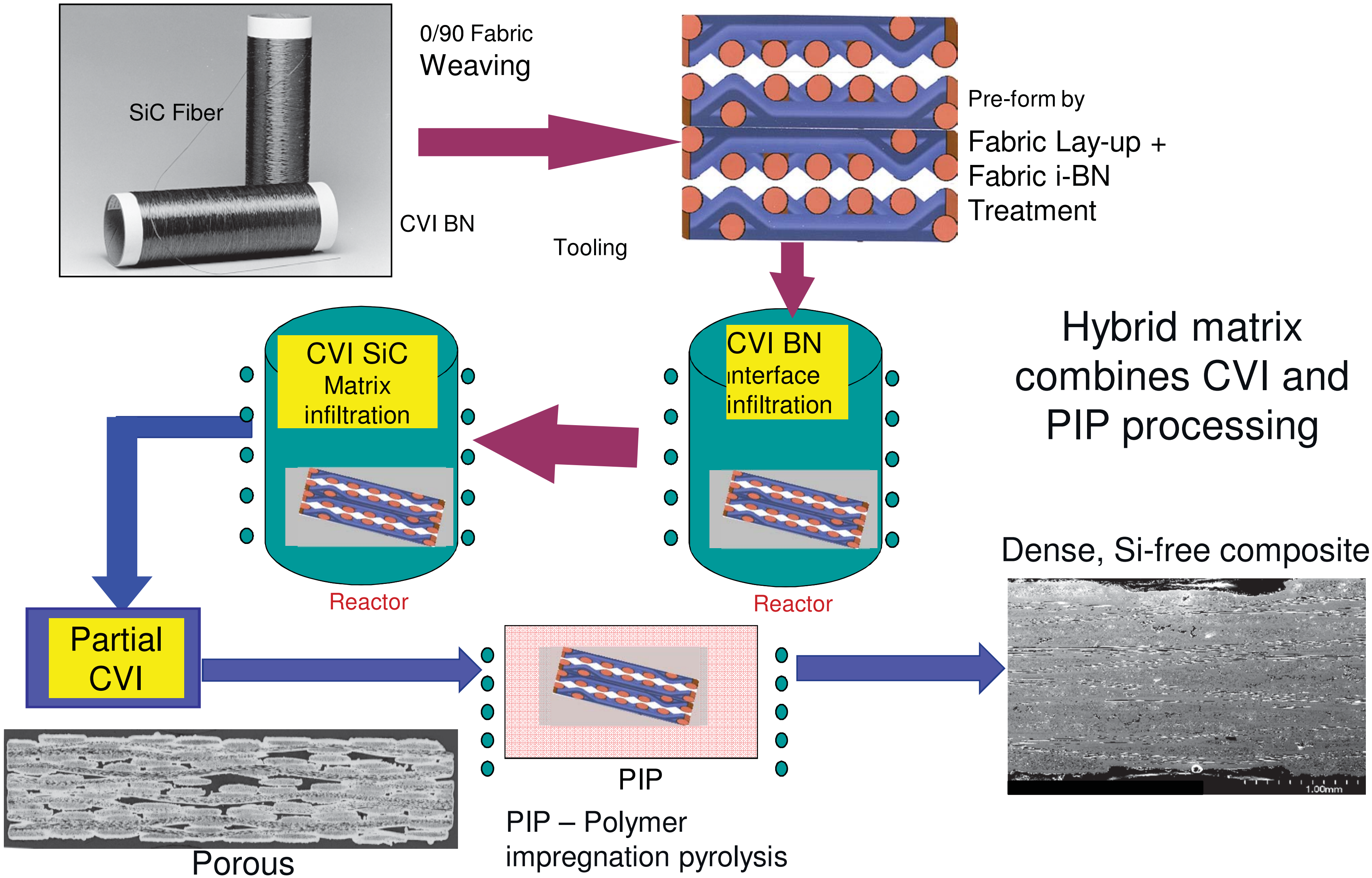
includes CMC research

Outline

- CMC Development & Characterization
- CMC / EBC Durability Modeling & Validation
- Additive Manufacturing

CMC Development and Characterization

Hybrid Process for Dense SiC / SiC Composites



2700^{0}F CMC Development and Characterization

Objective: Develop durable 2700^{0}F CMC for turbine components

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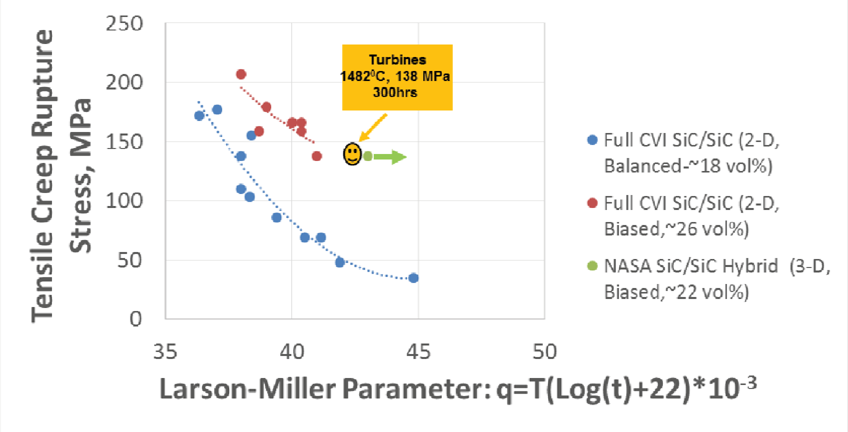
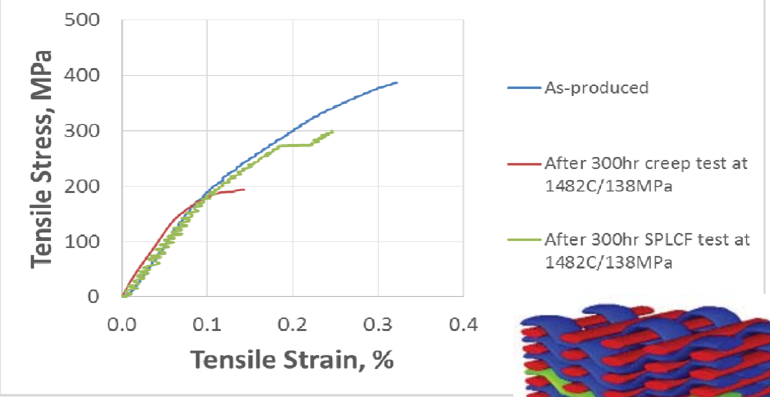
Approach

- Identify optimum constituents and processing methods
- Fabricate 1st generation 2700^{0}F CMC with (CVI+PIP) hybrid matrices and candidate 3D fiber architectures
- Characterize CMC properties and damage mechanisms under static and cyclic conditions for at least 300 hours at 2700^{o}F
- Fabricate 2nd generation 2700^{0}F CMC with optimized fiber architecture and constituents for component applications
- Characterize mechanical properties and damage mechanisms of optimized Gen-2 CMC under static and cyclic conditions.

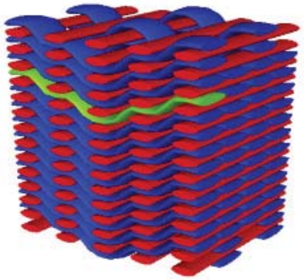


Generation 1 CMC has >300hrs life at 2700^{0}F / 20 ksi



Accomplishments

- Demonstrated 20 ksi / 2700^{0}F / 300 hours durability under creep, fatigue and (creep + fatigue) loading for CMC with hybrid matrix and Sylramic-iBN fibers
- Identified optimal fiber architecture (3D Modified Angle Interlock) for Gen-2 CMC with hybrid matrix and Hi-Nicalon-S fibers



Modified Angle Interlock fiber architecture

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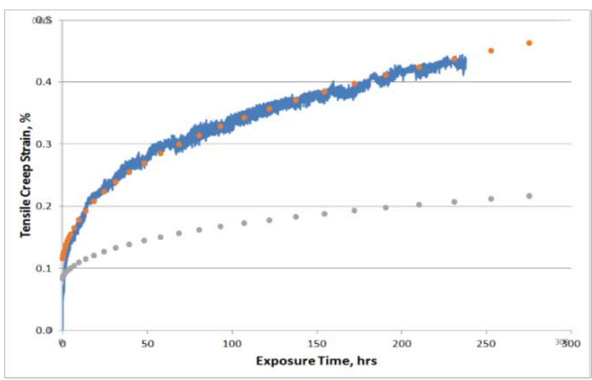
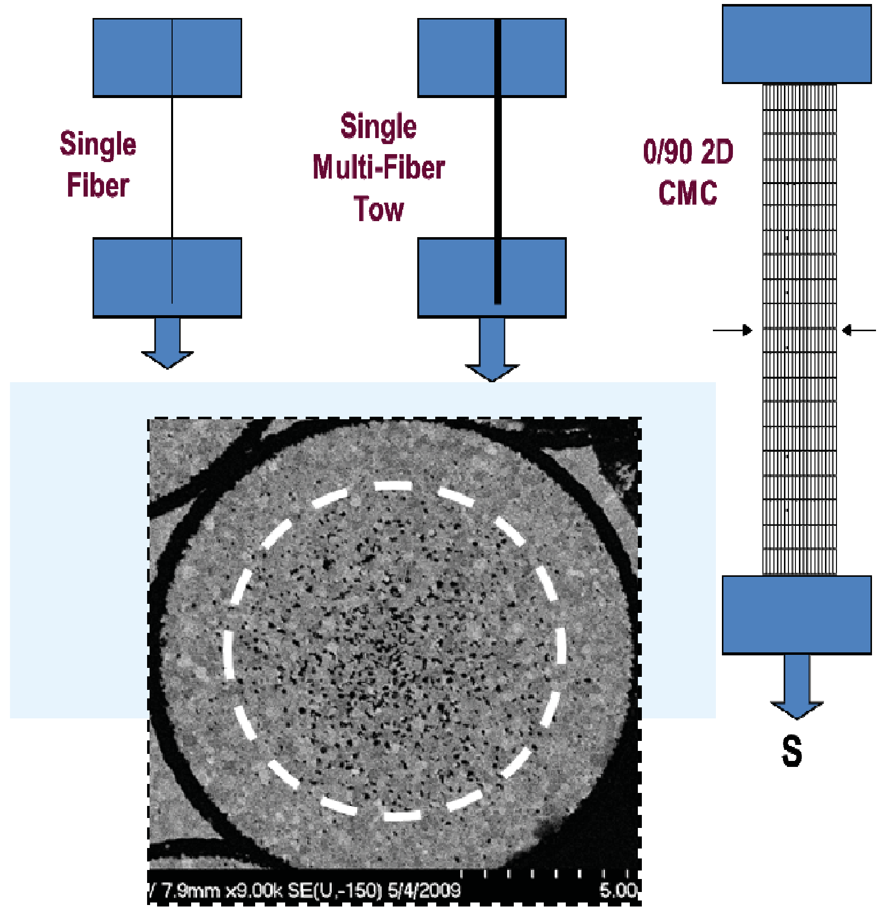
Fiber Research for 2700°F SiC/SiC CMC

Test and characterize key properties of potential 2700°F SiC fibers in order to:

- Understand basic mechanisms
- Develop approaches for property improvement
- Develop analytical fiber and CMC models for time-temperature deformation and rupture behavior





improve fiber processing to obtain uniform microstructure & optimal properties

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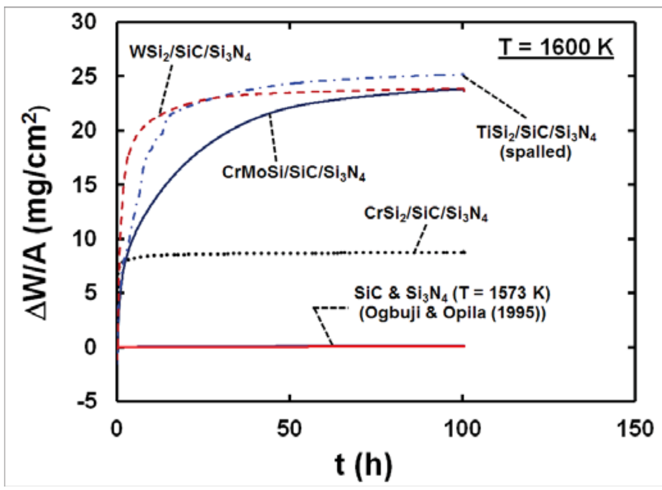
Toughened SiC matrix in development

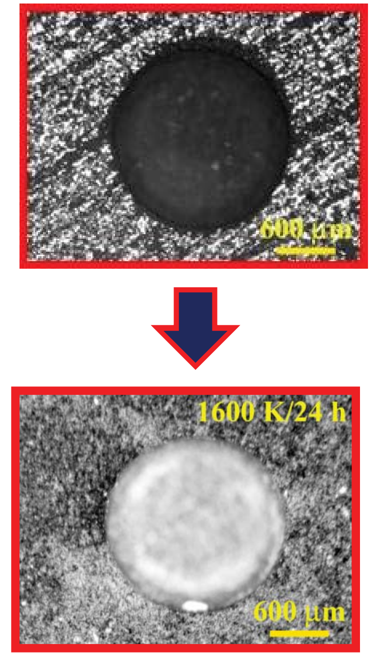
Desired matrix properties:

- Increased toughness for improved durability
- Dense matrix for high thermal conductivity

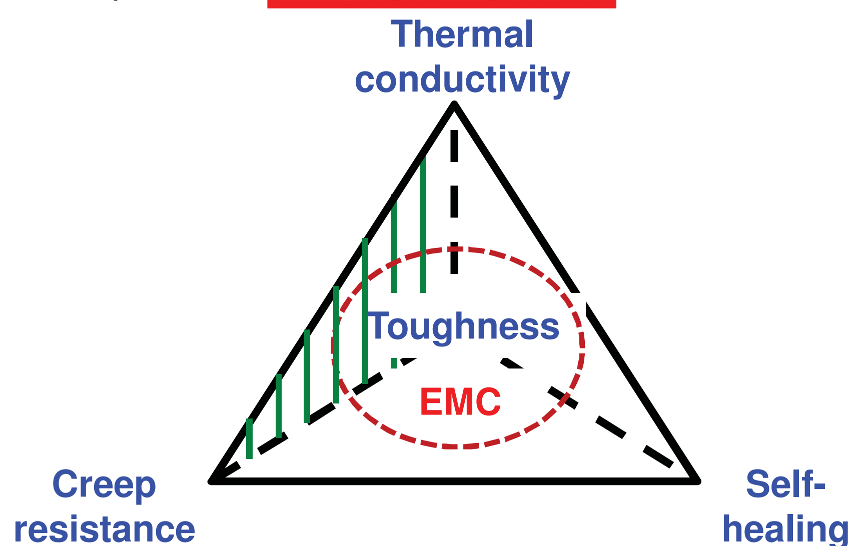


Isothermal oxidation of candidate matrix systems

Before Oxidation



After Oxidation



$CrSi_2$ / SiC / Si_3N_4 and CrMoSi / SiC / Si_3N_4 engineered matrices with crack blunting and self-healing capabilities are being developed

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CMAS interactions with EBC materials

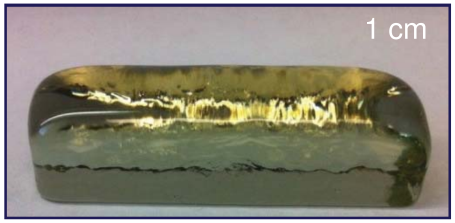
Characterization of thermal and mechanical properties of CMAS glass

- Fundamental knowledge of CMAS will help mitigate damage and improve durability of protective T/EBCs

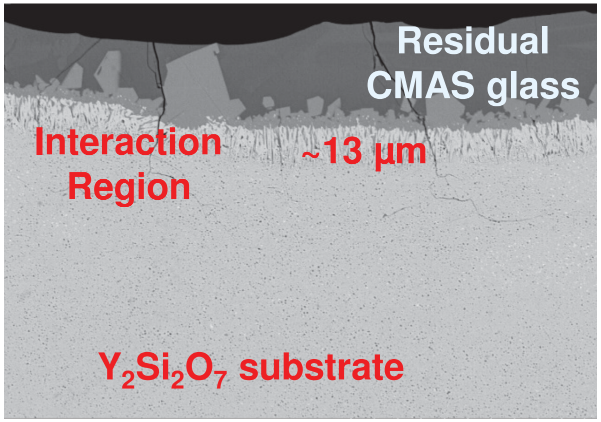
Interactions between CMAS and EBC

- EBC materials:
  - Yttrium disilicate ($Y_2Si_2O_7$)
  - Hafnium silicate ($HfSiO_4$)
  - Ytterbium disilicate ($Yb_2Si_2O_7$)
- Evaluate heat treated EBC substrates and pellets loaded with CMAS glass

Aircraft engine ingests sand on runway



Glass bar after melting of sand



$Y_2Si_2O_7$ substrate exposed to CMAS at 1200°C for 20h

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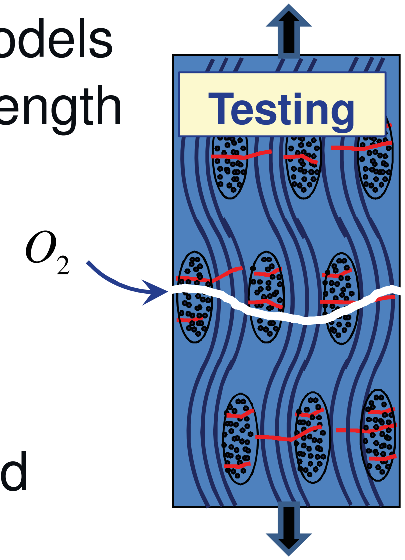
CMC / EBC Durability Modeling & Validation

Modeling Environmental Effects on SiC/SiC CMCs

Modeling Supported by Characterization of Degradation Mechanisms

Objective: Determine oxidation mechanisms and develop models for the mechanical-oxidation-creep interactions that affect strength and life of SiC_f /BN/SiC CMCs



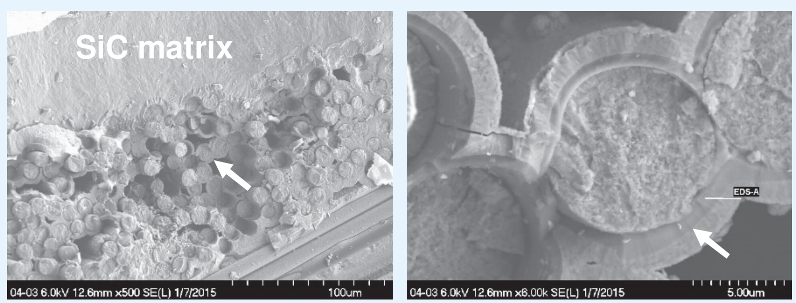
Approach:

- Perform parallel and correlative *experimental* and *numerical analysis* studies.
- Build on the numerical solution methodology developed previously for the oxidation of C/SiC CMCs.

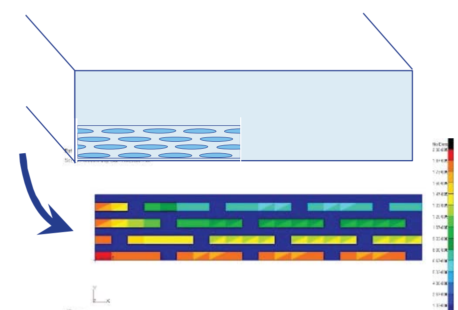
Testing and **Characterization** iterate **Modeling and Validation**

Notched CVI SiC/SiC Sample:

- **Pre-cracked to 250 MPa**
- **Held 300 h, 815°C (air), 172 MPa**



Fracture surface: oxidation of BN interphase near surface of specimen



Prediction of BN oxidation patterns at 30 h, 815°C (air)

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CMC / EBC damage progression modeling & validation

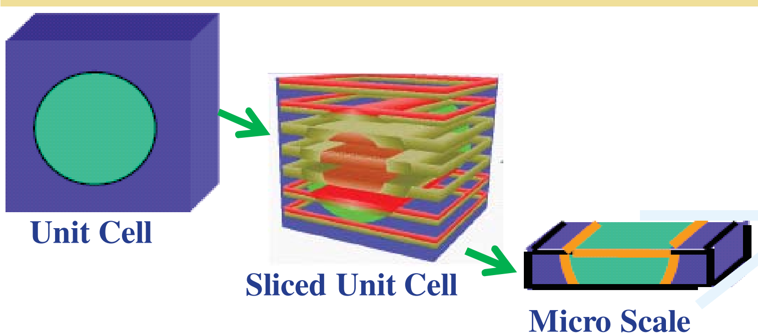
Objective: Model damage accumulation and failure process in EBC/CMC using progressive failure analysis

Approach:

- Select well characterized materials for model EBC/CMC system: plasma sprayed BSAS coating on SiC/SiC substrate

Model System: BSAS-SiC/SiC

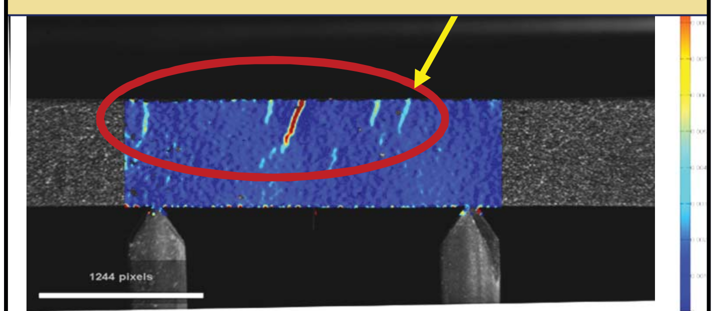
PFA approach: FEM results to the Micro Scale



- Create FEA model for EBC/CMC using a unit cell representation

- Validate damage progression results using Digital Image Correlation

Digital Image correlation (DIC): High local strains indicated at failure



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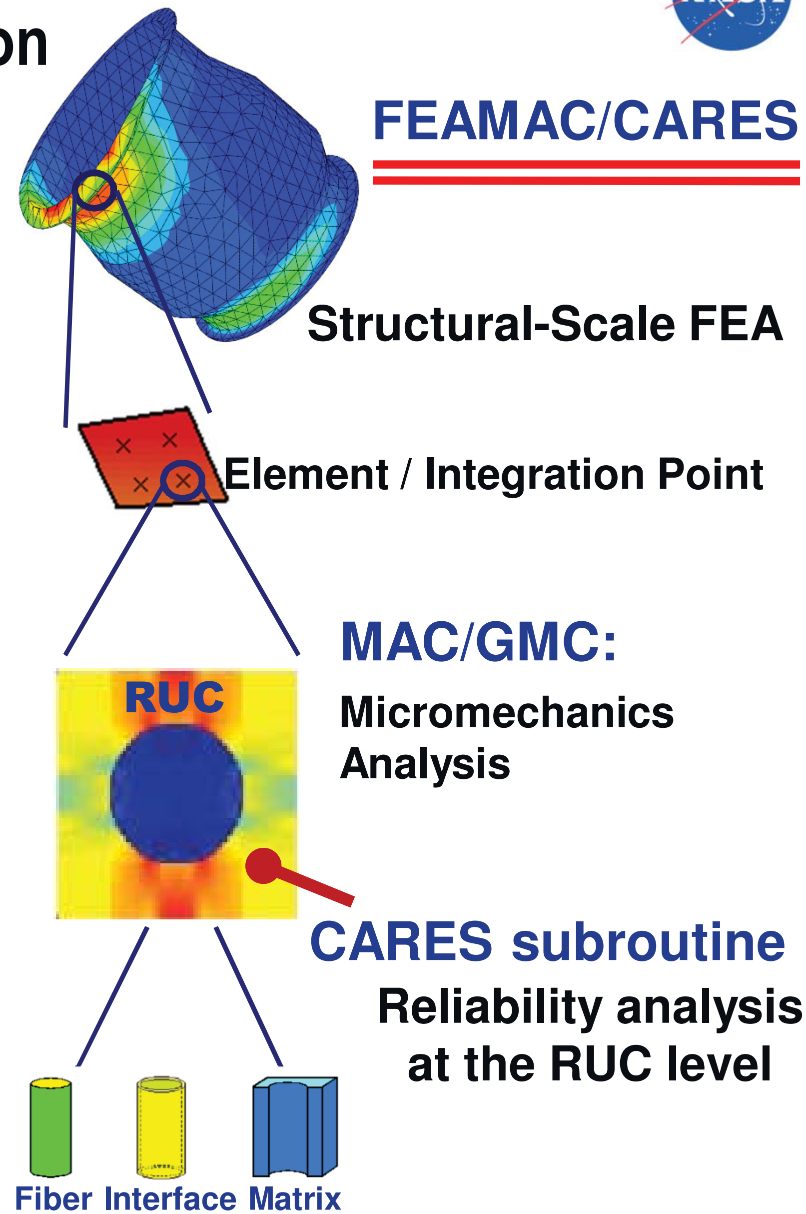
A new approach for CMC life prediction

➢ *Combine CARES, MAC & FEA codes*



CARES: *monolithic ceramics*

- Probabilistic strength
- Mechanistic-based multiaxial failure model
- Efficient life prediction algorithm
- Isotropic and *transverse isotropy*

MAC/GMC: *composite micromechanics*

- Micromechanics
- Accurate RUC stress fields
- Flexibility in RUC designs
- Progressive damage capability
- Computationally efficient

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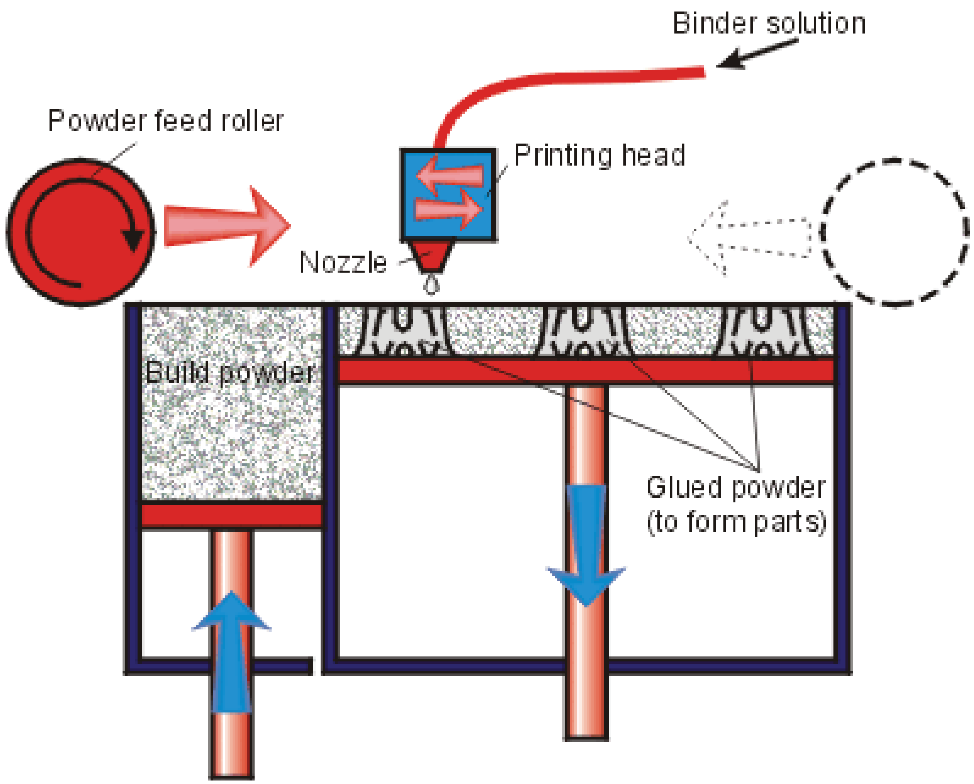
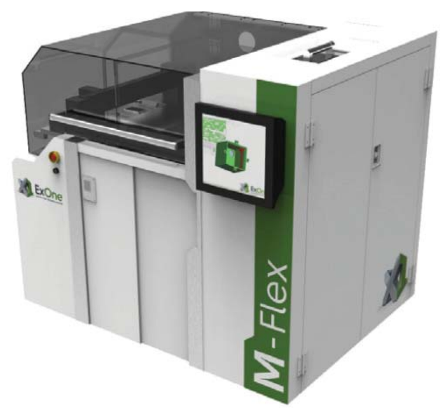
Additive Manufacturing for CMCs

Binder Jet process was adapted for fabricating Ceramic Matrix Composites

An inkjet-like printing head moves across a bed of ceramic powder depositing a liquid binding material in the shape of the object's cross section



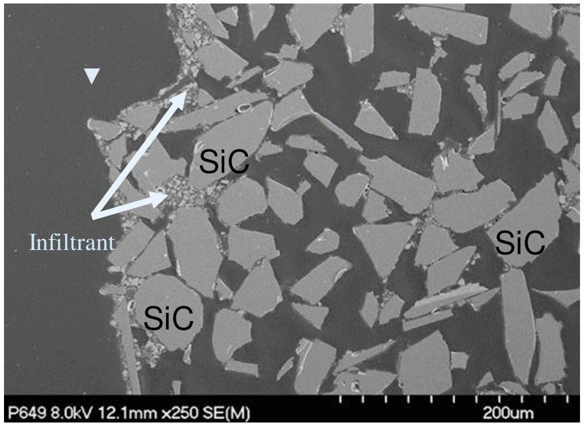


ExOne's M-Flex print machine

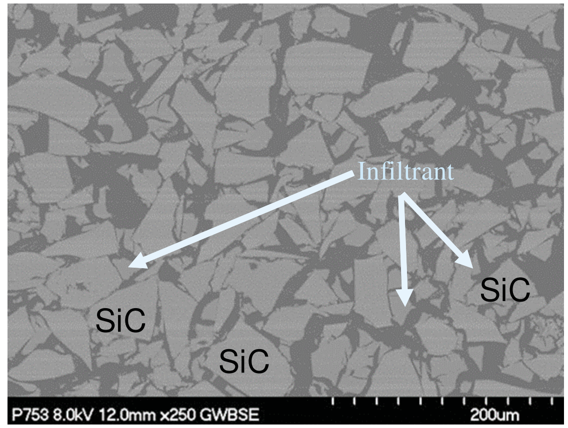
Binder jet printing allows for powder bed processing with *tailored binders* and *chopped fiber reinforcements* for fabricating advanced ceramics

Fabrication of chopped fiber CMC by Binder Jet + polymer infiltration

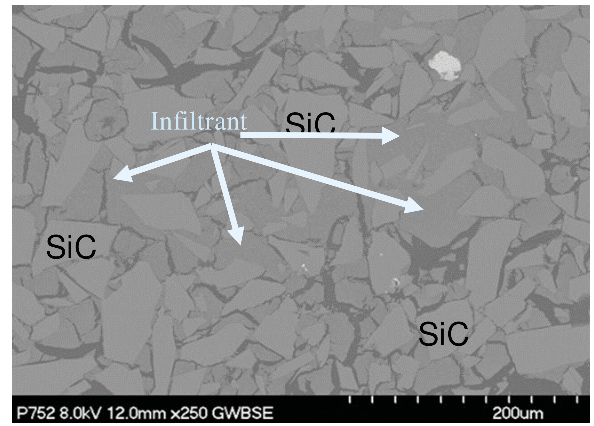
1. Densify SiC matrix with successive infiltrations



First iteration shows loose particle packing and limited infiltration

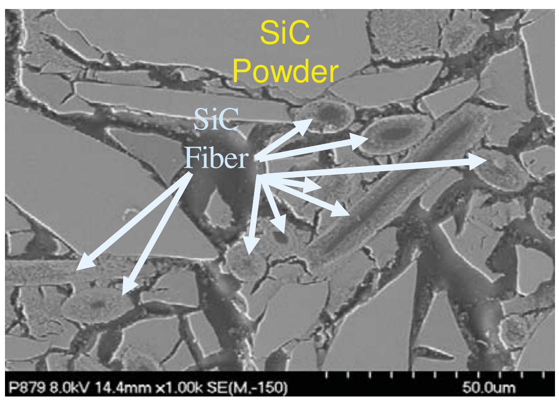


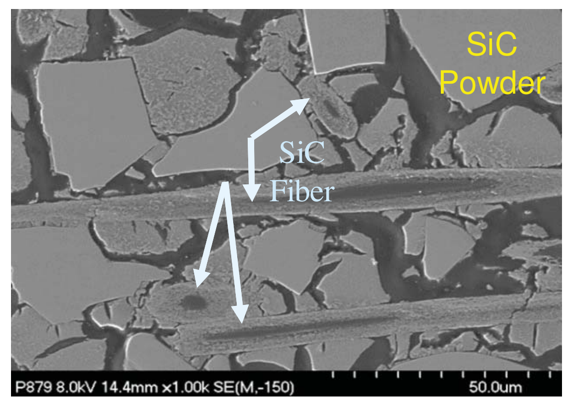
Blending two powder sizes improves packing and infiltration



Loading infiltrant with smaller dia powders further improves density

2. Add chopped fiber to Binder Jet powder bed

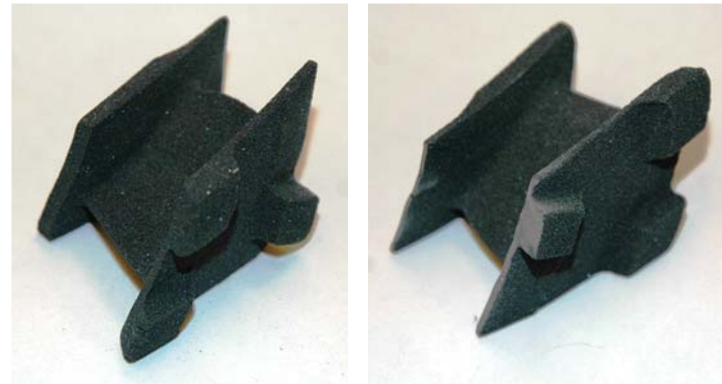




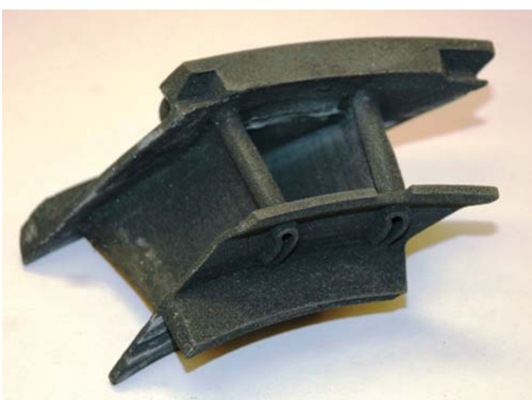
CMC with 35 vol% SiC fiber loading (1000x magnification)

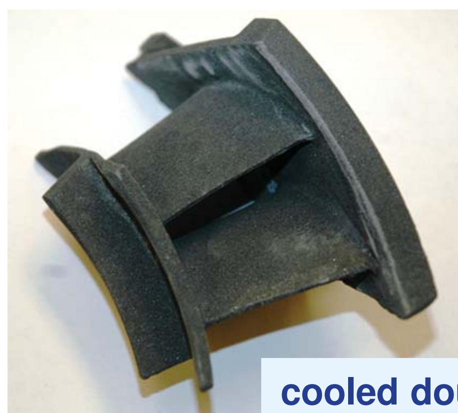
The first CMC turbine engine components by additive manufacturing

high pressure turbine nozzle segments



first stage nozzle segments





cooled doublet nozzle sections

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SiC/SiC CMCs have 20% chopped SiC fiber

Summary

CMC Development & Characterization

- Measured static and fatigue properties of “Gen 1” Hybrid-matrix CMC to 2700^0F
- Characterized durability and failure mechanisms of pre-cracked MI and CVI SiC/SiC composites under creep and fatigue loading
- Developing an approach to optimize fiber and matrix composition, processing and properties to minimize CMC creep deformation and introduce self-healing and crack blunting capabilities.
- Measured properties of CMAS (calcium-magnesium aluminosilicate) glass and characterized interaction with EBC coatings
  - measured modulus, hardness, strength, toughness, CTE and viscosity

CMC / EBC Durability Modeling & Validation

- Developing models of oxidation-creep interactions that affect strength and life of SiC / SiC CMCs
- Using progressive failure analysis and Digital Image Correlation to understand CMC/EBC degradation process
- Augmented micromechanics-based life prediction code (MAC/GMC) with stochastic strength model to simulate CMC damage progression

Additive Manufacturing

- Developed additive manufacturing processes to fabricate SiC / SiC composites

NASA GRC Focus in 2015

CMC Development & Characterization

- Fabricate "Gen 2" Hybrid-matrix CMC, measure static and fatigue properties
- Optimize fiber composition & processing to minimize creep deformation
- Evaluate toughened matrix composite with SiC fiber

CMC / EBC Durability Modeling & Validation

- Validate SiC/SiC oxidation-creep interaction model with test data
- Validate CMC/EBC failure analysis with NDE and Digital Image Correlation
- Validate MAC/GMC life prediction code with damage progression data

Additive Manufacturing

- Measure mechanical properties of initial SiC/SiC composites and optimize Binder Jet process